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ALTERATION OF SURFACE OPTICAL PROPERTIES BY HIGH-SPEED MICRON SIZE PARTICLES

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ALTERATION OF SURFACE OPTICAL PROPERTIES

BY HIGH SPEED MICRON SIZE PARTICLES

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SUMMARY

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Micron-size particles were accelerated by aerodynamic drag to gas speeds in a 3-inch shock tube to simulate some aspects of micrometeoroid erosion. A streak camera technique was used to make velocity measurements in the gas-heated, radiating cloud of particles. Good agreement was obtained between measured and theoretically predicted velocities. Integrated density measurements were made by collecting the particles on disk collectors.

Aluminum and aluminum-coated disks were placed in the shock tube and exposed to bombardment by a known number of particles with known velocity, size, and composition. These experiments yielded the following results:

1. Bombardment of polished metallic surfaces by high-speed, micron-size particles causes reduction in average reflectivity, $\bar{\rho}$, of the surface. This reduction can be correlated with the kinetic energy of the bombarding particle cloud, $\mathcal{E}$, by an expression of the form

$$\bar{\rho}(\mathcal{E}) = \bar{\rho}_i\left[1 - \left(1 - \frac{\bar{\rho}_\infty}{\bar{\rho}_i}\right)\left(1 - e^{-S\mathcal{E}}\right)\right]$$

2. This correlation indicates that the measured kinetic energy flux of micrometeoroids in the vicinity of the Earth in the range 10^{10} to 10^{-8} g will reduce the reflectivity of a polished aluminum surface to half its original value in about 3 years. Although the results of experiments on nine major satellites have not detected particles smaller than 10^{-10} g, an extrapolation of the existing data, with the assumption that particles of 10^{-11} g do exist at the extrapolated flux, reduces this damage time to about 7 months.

3. Coatings of 8600 Å aluminum on a 15/16-inch-diameter Bakelite disk were removed by particle clouds with kinetic energy of less than 2 joules, an amount less by an order of magnitude than the energy required to remove these coatings by evaporation.

AUTHOR

INTRODUCTION

One of the hazards encountered by space vehicles, particularly when they are traveling in the vicinity of the Earth, is that of collision with micrometeoroids. The latest data[1] on space conditions indicate that flux rates become appreciable for particle mass of 10^{-6} g. (A particle of mass 10^{-10} g hits an area 1 cm square about 10 times per day.) The relative speeds of these particles, with respect to the Earth, range from about 30,000 to 200,000 ft/sec, and these particles are estimated to have densities between 0.05 to 5 g/cc. The effect on the surface optical properties of materials after prolonged exposure to the high-speed micrometeoroid environment of space is not known. It is therefore desirable to simulate this space condition and study the effects in the laboratory. This can be done by choosing particles of known mass and composition and accelerating these particles to speeds comparable with those that exist in space. Bombardment of surfaces of interest by these particles causes damage to the surface optical properties, which can be measured and which can therefore be transformed into quantitative information concerning the degradation of such surfaces in space.

A facility that can be used in the laboratory to simulate these conditions is the shock tube. The use of aerodynamic drag of a short-duration flow in a shock tube as a means of accelerating small particles to shocked gas speeds was studied both analytically and experimentally at the Lewis Research Center. Although the particle speeds are lower in our present shock tube than those existing in space they were sufficiently high to make hemispherical craters (particle velocity greater than one-half the sound speed in the target material) in aluminum targets[2] ($V/C \geq 0.5$). Various polished aluminum and aluminum-coated disks were placed in the shock tube and exposed to the high-speed particles. Experimental damage to the targets was determined by measuring changes in the optical properties of the various surfaces with a spectral reflectometer. The results of these damage studies are presented herein together with a correlation that permits prediction of time variation of surface reflectivity in space.

SYMBOLS

b	$\dfrac{3\pi\eta D}{k_m}$
C	velocity of sound
C_p	specific heat of particle
C_1	$\dfrac{2r^2 C_p \rho_p}{3k}$
D	particle diameter
E	minimum energy density needed to expose Royal X Pan film
$\mathcal{E}$	$\sum_i \frac{1}{2} m_i V_i^2$

F_d	drag force
K	$\frac{b}{m} = \frac{18\eta}{k_m \rho_p D^2}$
k	thermal conductivity of accelerating gas
k_m	Cunningham-Millikan correction factor, $1 + \frac{0.16\times10^{-4}\text{cm}}{D}\left(\frac{T}{To}\right)\left(\frac{P_o}{P}\right)$
M	Mach number
m	particle mass
m_i	mass of i^{th} particle
R	distance from particle to lens of streak camera
r	particle radius
r_l	radius of camera lens
S	constant in exponent of eqs. (6) and (7)
T_e	gas temperature
$T_{p,1}$	temperature of particle in hot gas
$T_{p,2}$	temperature required for particle traveling at V_p to radiate minimum energy needed to expose Royal X Pan film
T_r	room temperature
t	time
V	velocity
V_g	gas velocity
V_i	velocity of i^{th} particle
V_p	particle velocity
X_p	distance from injection point of particle
η	viscosity of gas
ρ_p	density of particles
$\bar{\rho}$	average reflectivity

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$\bar{\rho}_f$ final average reflectivity

$\bar{\rho}_i$ initial average reflectivity

$\bar{\rho}_\infty$ average reflectivity after infinite time

σ Stefan-Boltzmann constant

Acceleration of Particles by Shock Tube Flows

An analysis was made to determine the feasibility of accelerating particles in short duration shock tube flows. The accelerating force was assumed to be the aerodynamic drag of the high-speed gas acting on spheroidal particles placed in the stream. The results of a typical calculation of the predicted velocity as a function of the distance downstream of injection, is shown in fig. 1 for SiC particles 2 to 20 microns in diameter. The Reynolds number for these particles relative to the gas was sufficiently low during a large part of the accelerating process to warrant use of the well-known Stokes solution for the spheres given by the following equation:

$$F_d = b(V_g - V_p) = m \frac{d(V_g - V_p)}{dt} \tag{1}$$

The semiempirical Cunningham-Millikan correction factor for slip[3] was added in the b of eq. (1), but this factor was generally very close to 1.0.

The solid curves in fig. 1 are defined by eqs. (2) and (3) which are obtained by integrating eq. (1):

$$V_p = V_g(1 - e^{Kt}) \tag{2}$$

$$X_p = V_g t - \frac{V_g}{K}(1 - e^{-Kt}) \tag{3}$$

The temperature of an accelerating particle in the hot gas at time t is

$$T_{p,1} = T_e + (T_r - T_e)e^{-t/C_1} \tag{4}$$

The temperature required for a particle traveling at V_p to radiate the energy needed to expose the film at the focal plane of the streak camera is

$$T_{p,2}^4 = \frac{ER^2V_p(t)}{2.5\ \sigma r_l^2 D}$$

The visibility curve of fig. 1 is obtained by equating $T_{p,1}$ to $T_{p,2}$.

The contact surface in fig. 1 signifies the termination of the hot gas flow, (i.e., arrival of the cold-gas piston contact surface) which was calculated from the theory of ref. 4. This does not terminate the flow altogether, however, for behind the contact surface is the cold expanded driver gas (He) whose velocity is the same as the hot gas (air) for a time. Particles that are not at gas speed on arrival of the contact surface pass through the contact surface and are still accelerated, but at a slower rate, by the cold gas. This condition lasts until termination of the cold flow, usually determined by the arrival of the first expansion wave. When applicable, a calculation was made to obtain the limit of visibility for the heated particles being cooled by the cold driver gas to temperatures below visibility.

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Experimental Procedure

The short duration flow in a 3-inch-diameter shock tube was used successfully to accelerate the micron size particles used in this program. Helium at high pressure was used as the driver gas, and air was used in the low pressure section. A copper diaphragm separating the chambers was ruptured by an arrow head plunger. This system was very successful in initiating the flows while preventing any diaphragm particles from tearing loose and interfering with the experiment. An important feature of the experiment is the fact that the gas behind the shock is at a high temperature, and therefore not only accelerates the small particles but also heats them sufficiently to make their trajectories visible on film.

Particles to be injected into the stream were placed on the horizontal surface of a sharp-edged, thin plate located downstream of the diaphragm in the middle of the shock tube from which they were picked up by the high-speed flows.

Velocity measurements of the gas-heated, radiating cloud of particles were made with 1250 ASA film in a streak camera. Results of one of these velocity measurements are shown in fig. 2. The streaks were made by radiation given off by SiC particles in the size range from 2 to 14μ. The shock Mach number was 6.5, and the initial air pressure was 6.7 mm Hg. The velocity was measured from the speed of the film and the angle of a streak with the horizontal. The speed of the film is very accurately known (to a small fraction of a percent) from measurements of rotational speed of the exposing mirror beam (246 rps), and hence particle speeds are measured to good accuracy. Data obtained in this manner are shown as experimental points in fig. 1.

Particle distribution measurements were made by collecting the particles on various diameter disk collectors as shown in fig. 3. The collectors range in diameter from 1/2 inch to $3\frac{13}{16}$ inches and were coated with vacuum grease to insure capture of the particles. The coated disk collectors were weighed on an analytic balance before and after the bombardment by particles. The difference in weight gives the mass of parti-

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cles collected by each disk, and from this the radial density distribution. When no particles were injected, as accurately as could be measured, the weights of the collectors were unchanged. The mass of particles collected, normalized to the mass of particles collected on the largest size disk, is plotted against the diameter of the disk collectors in fig. 4. From fig. 4, it can be seen that the radial distribution of particles varied only slightly with the Mach number and was independent of the initial total mass of particles placed in the shock tube.

After the velocity, size range, composition, and number of particles striking a given area were determined from the above procedures, aluminum and aluminum-coated disks were placed in the shock tube and exposed to bombardment by the particles. Experimental damage to the targets was considered to be the measured change in the reflectivity of the surfaces. This was determined by making reflectivity measurements over the wavelength range from 1.5 to 15μ on the disks before and after bombardment.

DISCUSSION OF RESULTS

A number of experimental investigations[5,6] have shown that the shape of the cavity formed in the target by a hypervelocity projectile is hemispherical, and that, the volume of the cavity is proportional to the kinetic energy of the projectile.[7] The theoretical analysis of ref. 8 indicates that the crater depth is proportional to kinetic energy to a power. Hence, we have characterized the exposure to particle bombardment with the quantity $\sum_i 1/2\, m_i V_i^2$. This also allows a possible time-of-exposure scaling factor if kinetic energy flux in a given situation is known.

Six polished aluminum disks 15/16 inch in diameter were bombarded by SiC particles. Spectral reflectivity for these disks befor and after exposure is shown in figs. 5 to 7. Fig. 5 presents this data for a disk exposed to 0.27 mg of SiC accelerated to gas speed at a shock Mach number of 8.4, and shows a considerable reduction in reflectivity due to the exposure. Fig. 6 shows the reflectivity of a similar disk exposed to 0.7 mg of particles also accelerated at a shock Mach number of 8.4. The reflectivity in this case was reduced an even greater amount. Fig. 7 contains the results for a disk exposed to 0.7 mg of SiC particles accelerated by the gas behind a shock of M_S = 6.86. Here, too, the reflectivity was considerably reduced. The data on these figures show that at all wavelengths (1.5 to 15μ) there is a marked reduction in reflectivity as both the particle velocity and the number of particles are increased. A sample aluminum disk before and after bombardment is shown in fig. 8.

The ratio of the final to initial average reflectivity $\bar{\rho}_f/\bar{\rho}_i$ is plotted in fig. 9 against the total kinetic energy of the cloud of particles impinging on the disk. It will be noticed that reflectivity decreases as kinetic energy increases, and, at an energy of about 1 joule, the ratio $\bar{\rho}_f/\bar{\rho}_i$ has fallen to 0.8. Thus, our aluminum disk exposed to

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1 joule of high-speed particle bombardment, the reflectivity has dropped from 0.95 to 0.76. This is equivalent to an increase in emissivity of the disk from 0.05 to 0.24, a factor of approximately 5, in the measured range of the wavelengths between 1.5 and 15μ.

In fig. 10 is presented the average cumulative mass distribution of interplanetary dust particles in the vicinity of the Earth as compiled in ref. 1. By integration of the measured mass distribution of fig. 10 for the particle mass range from 10^{-10} to 10^{-8} g, and assignment to the particles of an average velocity of 30 km/sec, as in ref. 1, it was found that the $\sum_i 1/2\, m_i V_i^2$ falling on a 15/16-inch-diameter disk was equal to one and one-half joules at the end of a year. With kinetic energy as the appropriate independent variable for scaling damage, we find then that the time of exposure for a 15/16-inch-diameter disk equivalent to 1 joule is about 8 months in space in the vicinity of the Earth. Thus, by replacement of the energy coordinate of fig. 9 by the equivalent time, our laboratory experiment indicates that the damage to optical properties of polished aluminum surfaces in space is considerable ($\bar{\rho}_f/\bar{\rho}_i = 0.8$) at the end of 8 months.

The authors have shown in some unpublished work that the reflectivity of a surface exposed to particle bombardment may be expressed as

$$\bar{\rho}(\mathcal{E}) = \bar{\rho}_i\left\{1 - \left(1 - \frac{\bar{\rho}_\infty}{\bar{\rho}_i}\right)\left(1 - e^{-S\mathcal{E}}\right)\right\} \tag{6}$$

where $\bar{\rho}_\infty$ is the reflectivity of the surface after a very long (infinite time) exposure. If we assume $\bar{\rho}_\infty$ is zero (a blackbody) after a very long time, eq. (6) simplifies to

$$\bar{\rho}(\mathcal{E}) = \bar{\rho}_i e^{-S\mathcal{E}} \tag{7}$$

Plotted in fig. 9 is eq. (7) with $S = 0.211$, obtained from the value of $\bar{\rho}(\mathcal{E})/\bar{\rho}_i$ of the experimental curve at 1 joule. Equation (6) indicates that a reduction of the reflectivity to one-half the original value would occur in 3 years if $\bar{\rho}_\infty = 0.15$. This value is obtained by assuming that the target craters are coated by projectile material (ref. 5) and that the projectile material has a $\bar{\rho} = 0.15$, which is a reasonable value for a stony material.

It is important to make clear at this point that the limit of 10^{-10} g at the low end of the mass size range of meteoroids in space was chosen because ref. 1 (fig. 10) specifically limits the range at this lower end value. Although more than a dozen major space vehicles had instrumentation to measure the flux of such particles, no data are shown for particles smaller than 10^{-10} g. This does not mean, however, that such particles do not exist, but suggests instead that none of the instrumentation on board these satellites was sufficiently sensitive to detect particles below 10^{-10} g. It is also possible that particles in the detectable range hitting a surface at extreme glancing angles may cause some surface damage and yet not be detected by the satellite instrumentation. This last group, however, is probably very small since the results of ref. 5 indicates that detection would occur for particles above the normal detection limit except for quite oblique angles of arrival at the surface.

If the curve in fig. 10 is simply extrapolated in order to include particles to the size 10^{-11} g, the time equivalence is shortened by a factor of nearly 5. Thus, the estimate of a 3-year life to one-half of the original reflectivity might be reduced to only 7 months. Such an extrapolation is conservative however, since flux rates probably do not continue to rise so rapidly as in the 10^{-10} to 10^{-8} g range.

To determine the durability of coatings exposed to high-speed particle flows, two aluminum coated Bakelite disks were placed in the shock tube. The aluminum had been vacuum deposited on the Bakelite disks and the thickness of the coating measured with an interferometer. The aluminum coated disks were then placed in the shock tube with a special holder designed to insure against removal of the aluminum by the hot gas. Exposure to the shock tube flows without insertion of particles showed no damage to the coating. The results of the experiment with particles showed that all the 8600 Å thick aluminum coating was removed when the Bakelite coated disk was exposed to 0.9 mg of 2 to 14μ SiC particles at M = 6.8, corresponding to a total energy of 1.83 joules. Figure 11 shows the coated Bakelite disk before and after exposure. In figure 11(b) unexposed portions of the disk at support points still show the original coating. For another disk with a 4800 Å aluminum coating, all coating was removed with a 0.87-joule (0.27 mg at M = 8.6) bombardment. Thus, it was shown that typical aluminum coatings (8600 Å or less) on Bakelite could be removed entirely from the surface of the Bakelite with an exposure to particles of total kinetic energy about an order of magnitude less than the thermal energy required to remove these coatings by evaporation. Calculations of coating lifetimes from using heat of vaporization for removal energy would, therefore, give lifetimes that are much too high.

Material similar to that of the Echo I balloon (2200 Å aluminum evaporated on 1/2-in. Mylar) was also placed in the shock tube and exposed to particle bombardment. In this case no real simulation of the support of the material (as in a balloon) could be made. The material was instead stretched over a backing plate and exposed in this way to particle bombardment. The reduction in reflectivity measured by the spectrometer is shown in fig. 12. Unfortunately, this cannot be used to determine the life of the balloon reflectivity, but it does indicate that micrometeoroids, even if they do not puncture the balloon, will reduce reflectivity at a rate that should be noticeable over the life of the satellite.

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CONCLUDING REMARKS

Exposure of polished aluminum surfaces to bombardment by a cloud of high-speed particles of known total kinetic energy causes damage that can be fairly well predicted by eq. (6) or (7). With a reasonable assumption concerning the reflective properties of stony materials (the material of most meteoroids) a good estimate of the damage to metal surfaces in interplanetary space near the Earth is also made possible. This only requires that the compiled measurements of meteoroid flux from over a dozen major space vehicles be allowed as correct. Even considering possible limitations of these data, a useful estimate of damage to surface optical properties in space can be made. The estimates indicate that if changes in surface optical properties of 50 percent are allowable, only missions of over 7 months will be affected. If smaller changes in surface optical properties are not acceptable to satisfactory vehicle performance, missions for less than this time may be affected.

ACKNOWLEDGMENT

The authors wish to thank S. J. Pinali and R. H. Dobshaw whose help with the operation of the shock tube was invaluable. Evelyn Anagnostou developed her own technique for the measurements on the spectral reflectometer, and made the measurements for the data presented in this paper.

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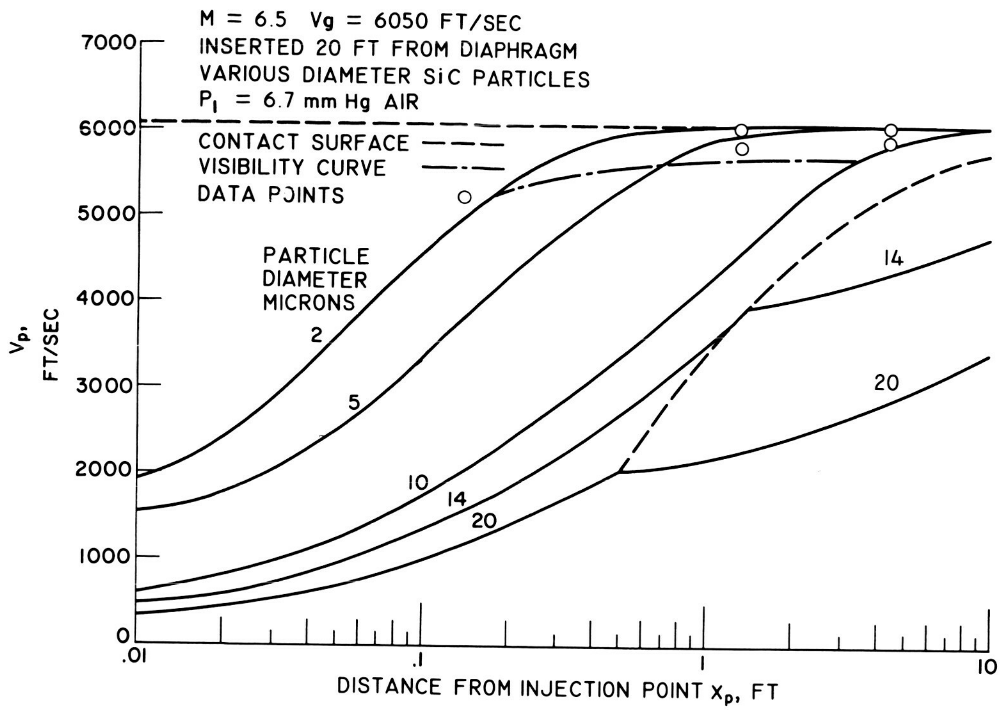

Fig. 1. - Velocity vs. position from injection point of SiC particles of various sizes for M = 6.5 and an initial air pressure of 6.7 mm Hg.

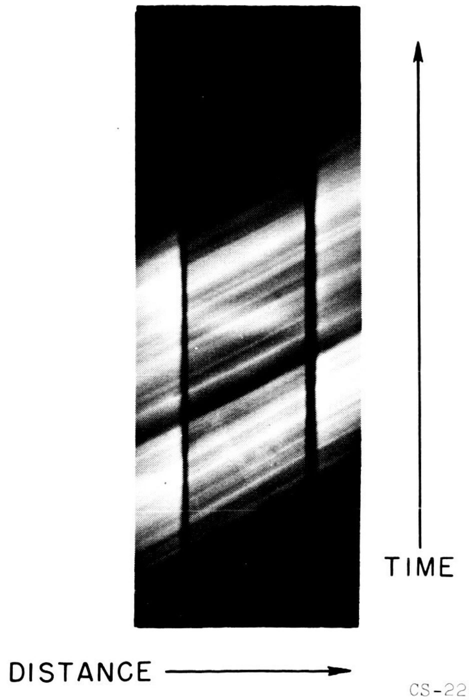

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Fig. 2. - Streaks made by radiation given off by 2 to 14 μ SiC particles at M = 6.5.

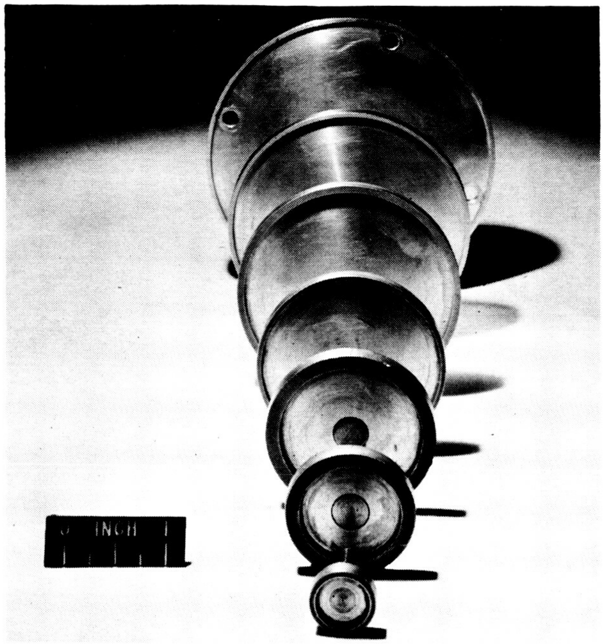

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Fig. 3. - Disk collectors of various sizes (1/2 in. to 3 13/16 in. in diam.) used to make integrated density measurements.

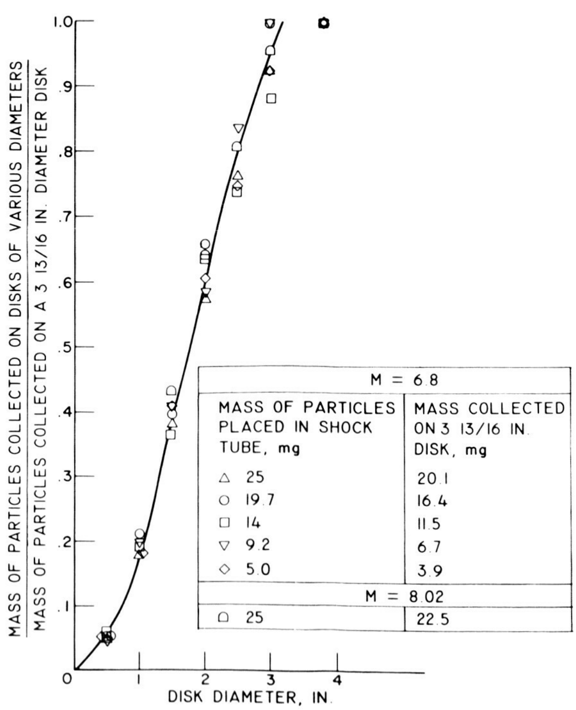

Fig. 4. - Mass of particles collected on the disks of various diameters normalized to total mass collected vs. the diameter of the disk collector.

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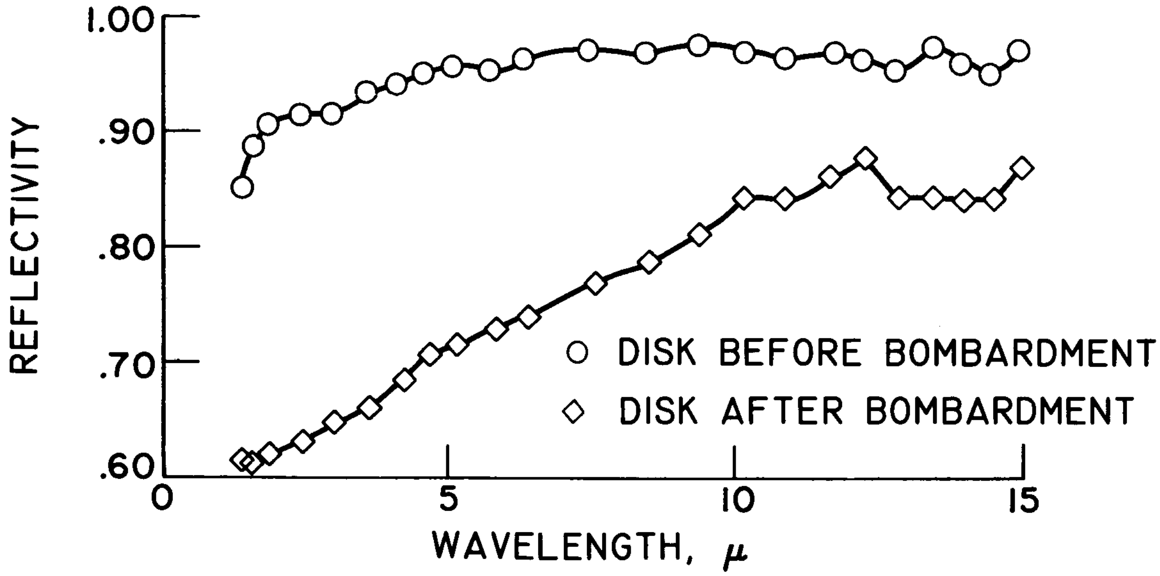


Fig. 5. - Spectral reflectivity vs. wavelength for a 15/16-in.-diameter aluminum disk exposed to 0.27 mg of 2 to 14 μ SiC particles at M = 8.4.

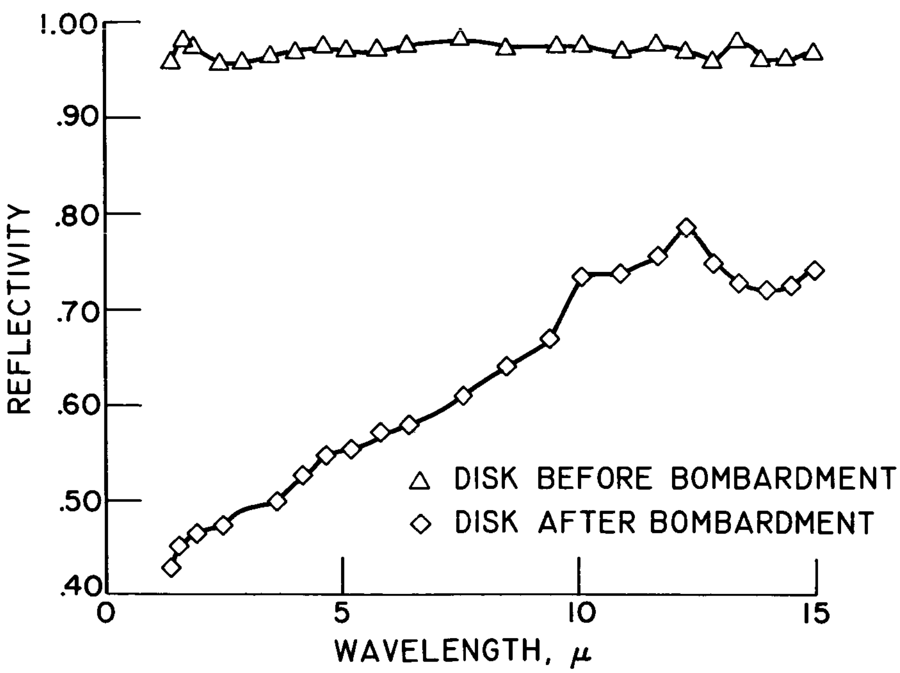


Fig. 6. - Spectral reflectivity vs. wavelength for a 15/16-in.-diameter aluminum disk exposed to 0.7 mg of 2 to 14 μ SiC particles at M = 8.4.

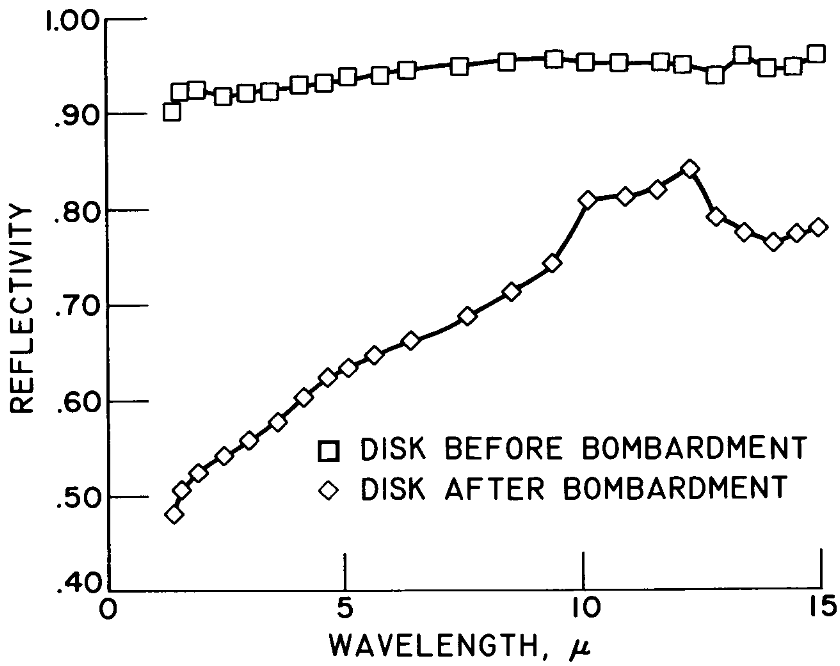
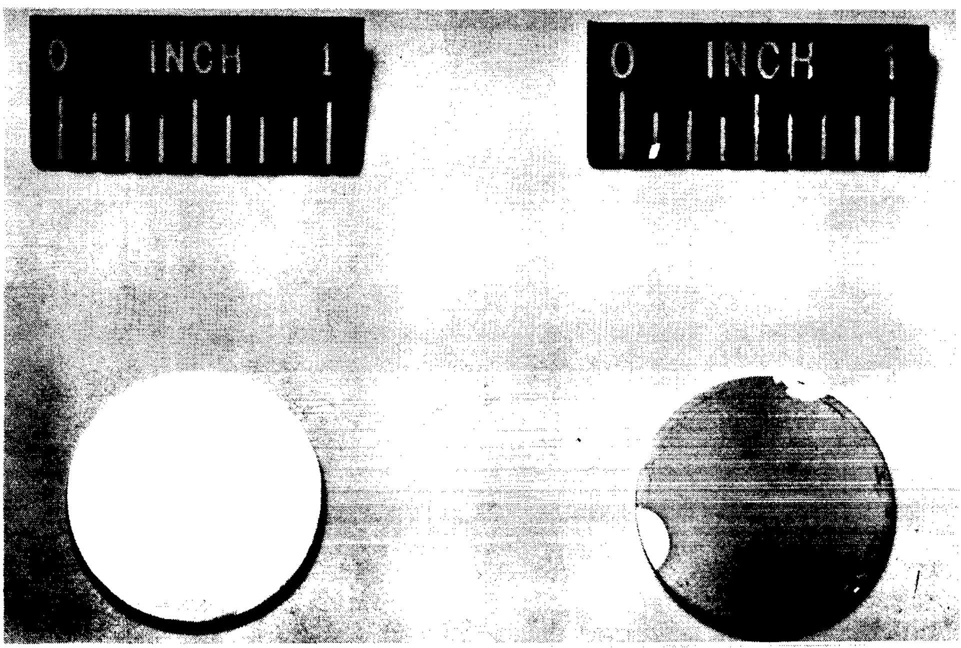


Fig. 7. - Spectral reflectivity vs. wavelength for a 15-16-in. - diameter aluminum disk exposed to 0.7 mg of 2 to 14 μ SiC particles at M = 6.86.



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(a) Before exposure. (b) After exposure.

Fig. 8. - Sample aluminum disk 15/16-in.-diameter before and after exposure to 2 to 14 μ SiC particle flows.

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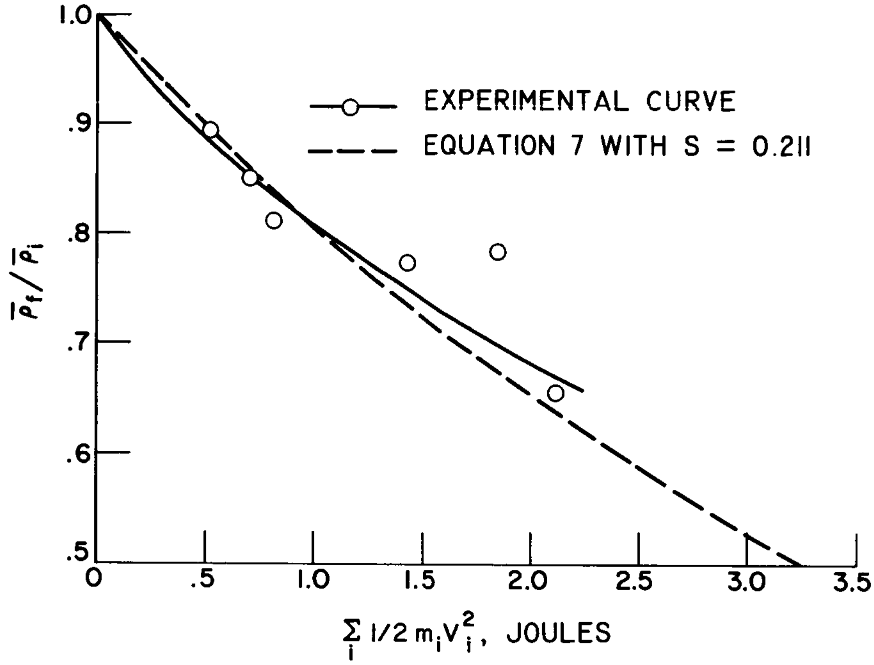


Fig. 9. - Ratio of final to initial average reflectivity $\bar{\rho}_f/\bar{\rho}_i$ vs. total kinetic energy ($\sum_i 1/2\, m_i V_i^2$) of the cloud of 2 to 14 μ SiC particles impinging on 15/16-in.-diameter aluminum disks.

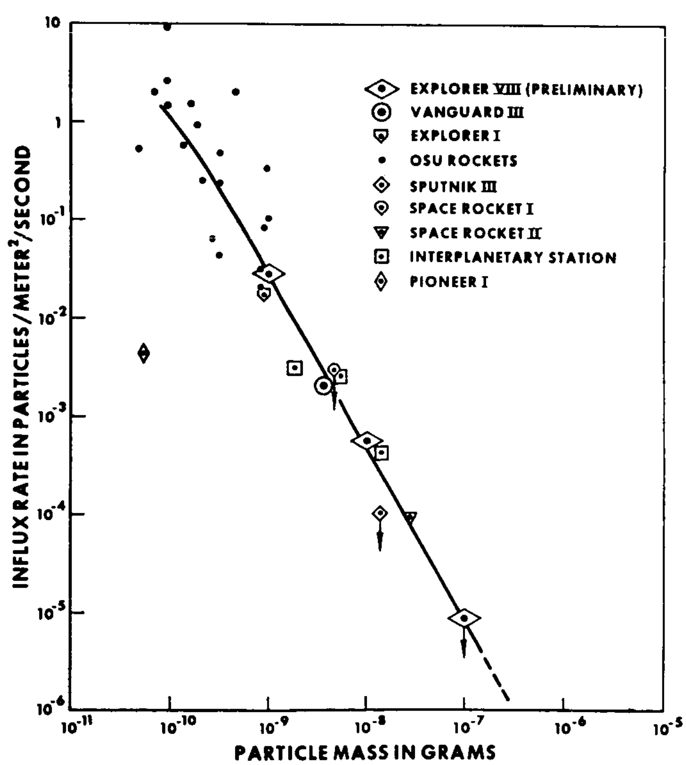
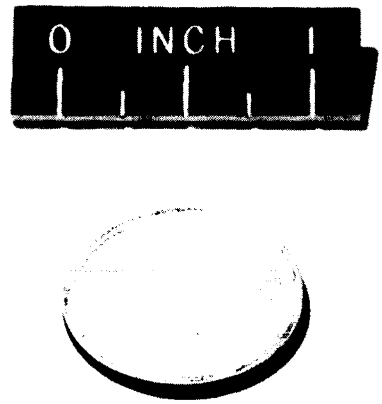


Fig. 10. - The average cumulative mass distribution established by direct measurements from microphone systems for interplanetary dust particles in the vicinity of earth.



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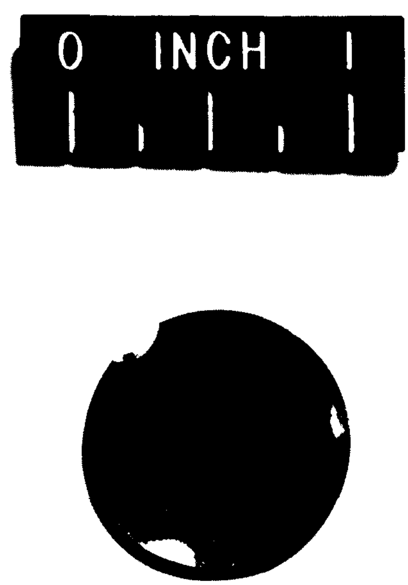
(a) Bakelite disk coated with 8600 A of aluminum.

Fig. 11. - Effect of exposure to particle bombardment on aluminum coated bakelite disk.



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(b) Same bakelite disk after exposure to 2 to 14 μ SiC particles at M = 6.8.

Fig. 11. - Concluded. Effect of exposure to particle bombardment on aluminum coated bakelite disk.

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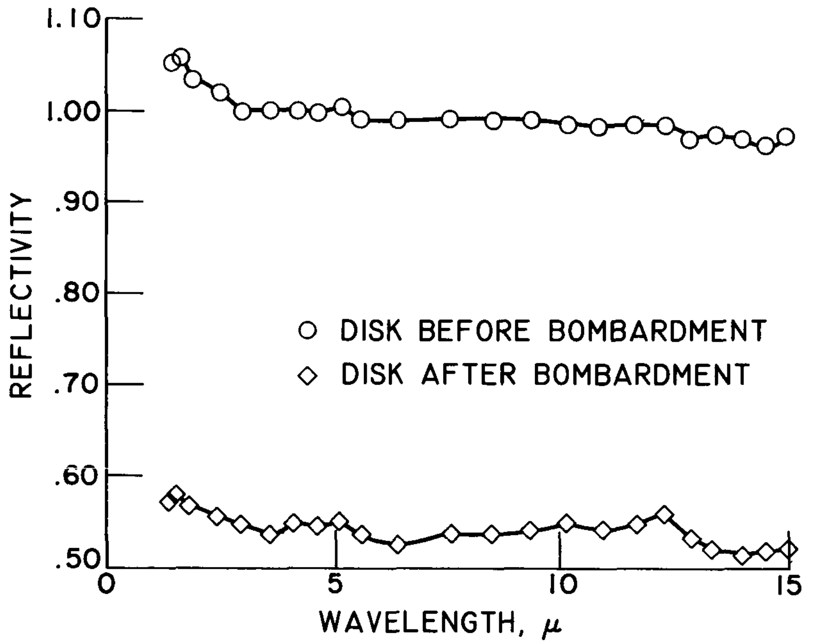

Fig. 12. - Spectral reflectivity vs. wavelength for a 15-16-in.-diameter disk of 1/2 mil mylar coated on both sides with 2200 A of aluminum and exposed to 0.7 mg of 2 to 14 μ SiC particles at M = 8.98.

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